Towards Accurate Uncertainty Estimates in High-Fidelity Radiation Transport Simulations of Fusion Power Plants

IAEA Digital Engineering Workshop, Cambridge, MA

December 10, 2025

Ethan Peterson[1,2], Grégoire Biot[1], Collin Dunn[2], Bamidele Ebiwonjumi[2], Jack Fletcher[2], Paul Romano[3], Stefano Segantin[2], Patrick Shriwise[3] , John Tramm[3], Jiankai Yu[1]

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~~Towards Accurate Uncertainty~~
~~Estimates in High-Fidelit~~
~~Radiation Trans~~
~~Simulati~~

Make simulations do more way faster

nbridge, MA

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Outline

- Radiation transport challenges for fusion power plants
- Workflow developments (R2S and D1S) in OpenMC
- Integration with discontiguous UM support through XDG
- SPARC example analyses and performance comparisons
- Nuclear heating and SDR UQ + automated CAD-first benchmarking

Why are there unique simulation challenges (and opportunities) for radiation transport in fusion power plant design?

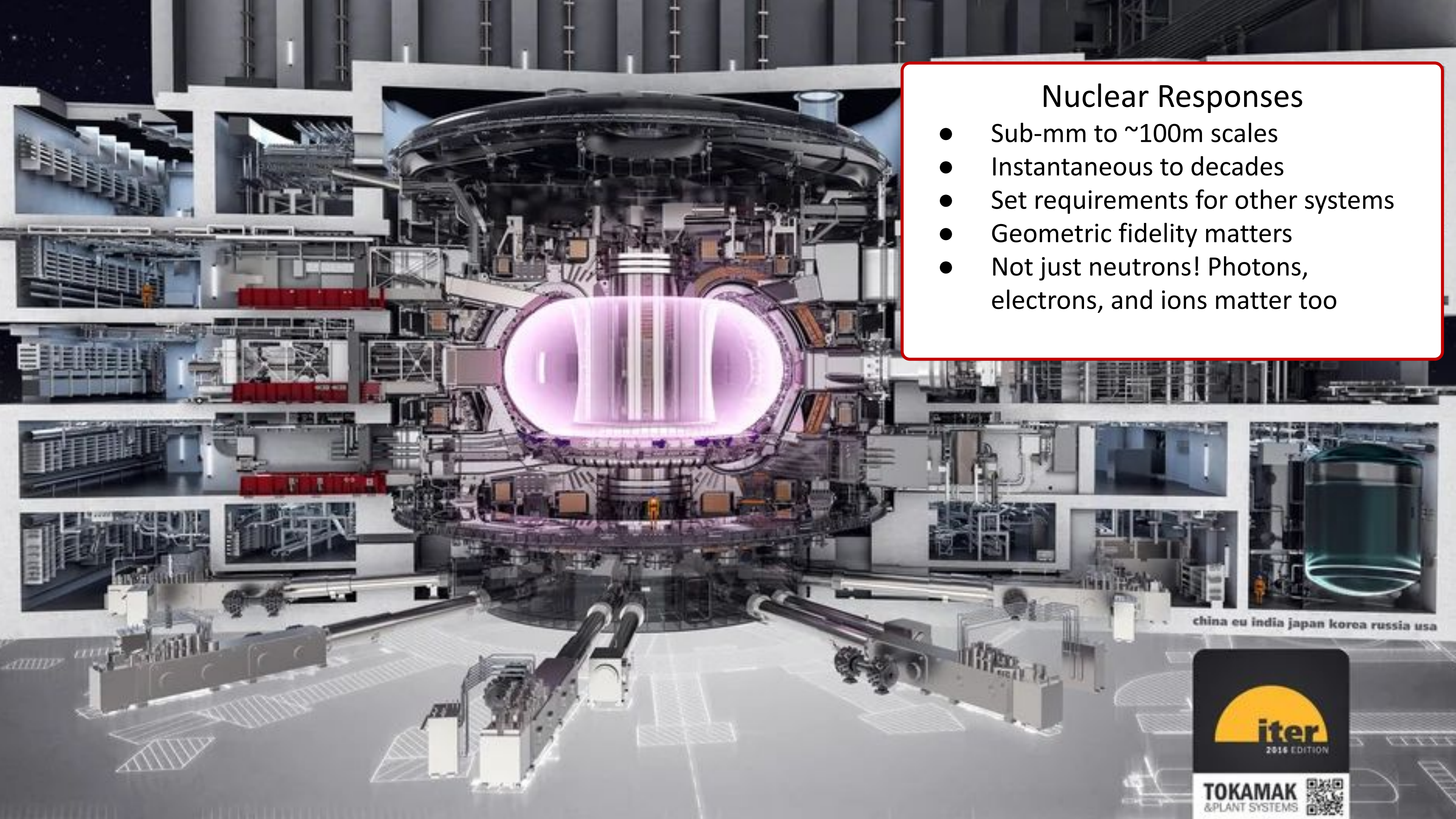
Scale & Detail

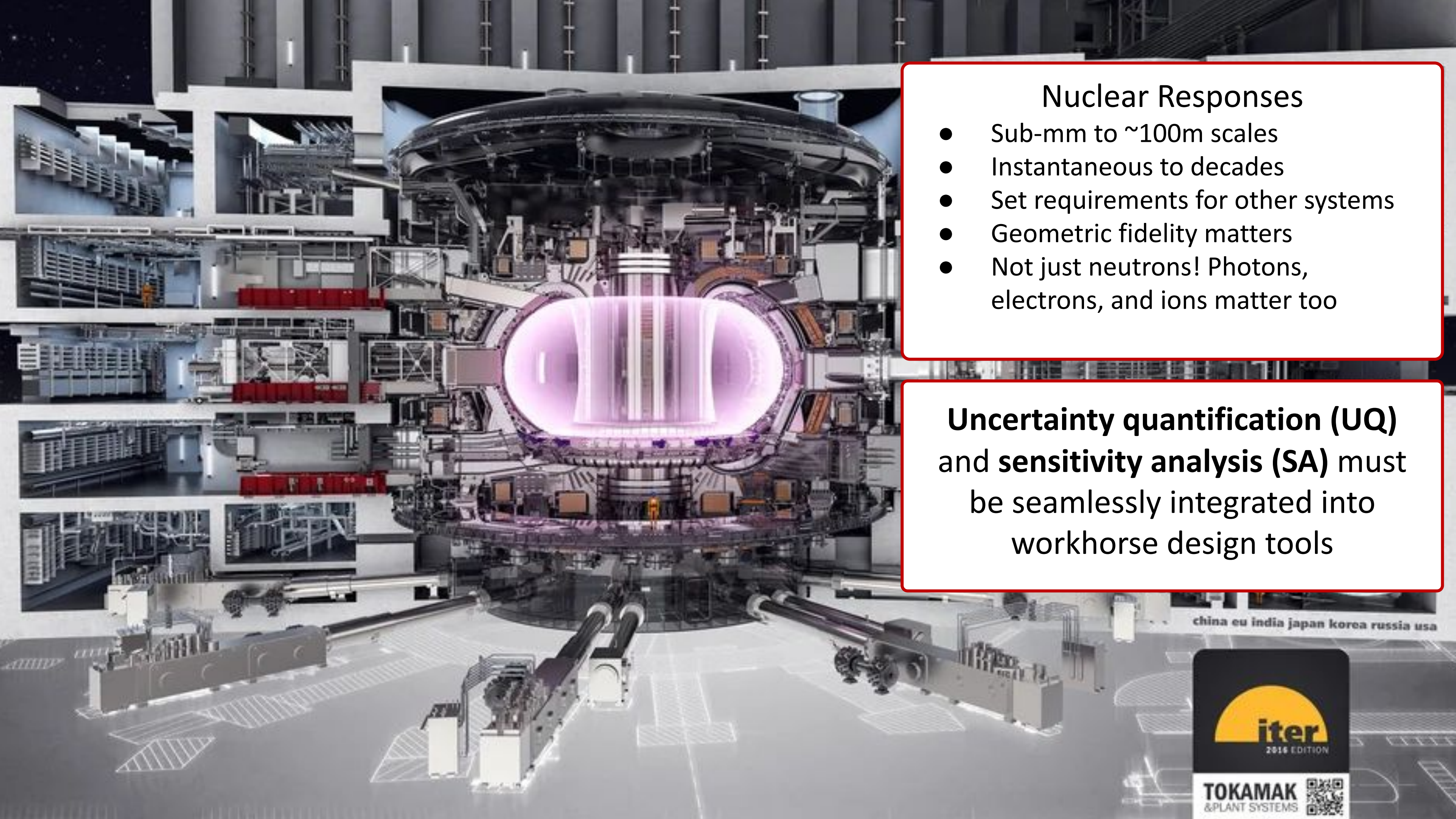
Scale & Detail

Geometry Representation Matters!

Nuclear Responses

- Sub-mm to ~100m scales
- Instantaneous to decades
- Set requirements for other systems
- Geometric fidelity matters
- Not just neutrons! Photons, electrons, and ions matter too





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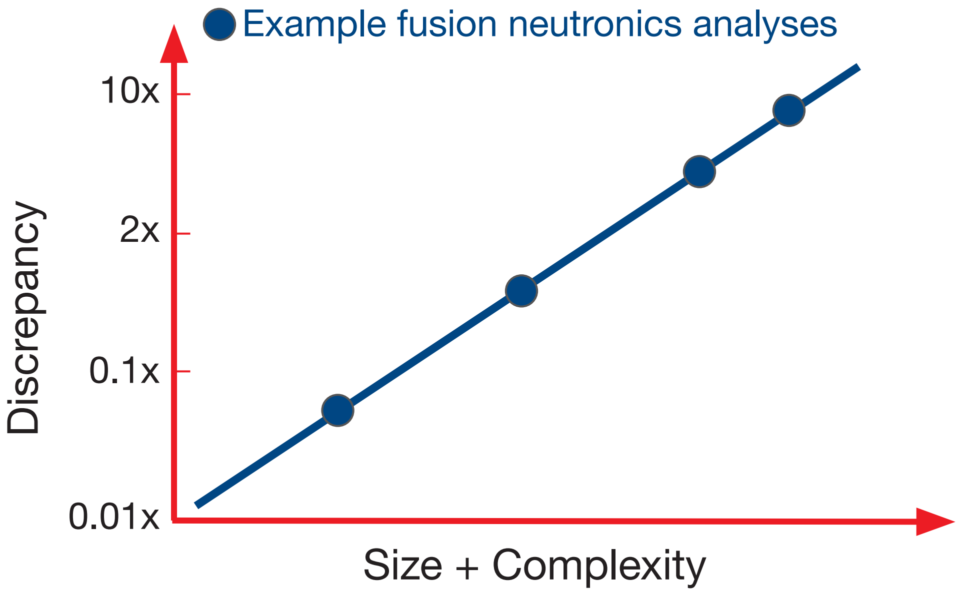
Uncertainty quantification (UQ) and **sensitivity analysis (SA)** must be seamlessly integrated into workhorse design tools

Integrated UQ is critical to improving predictive modeling

Uncertainties come from many places: nuclear data, material and geometry specifications, method approximations.

Discrepancies between experiments and computational models naturally increases as the size and complexity of models increases.



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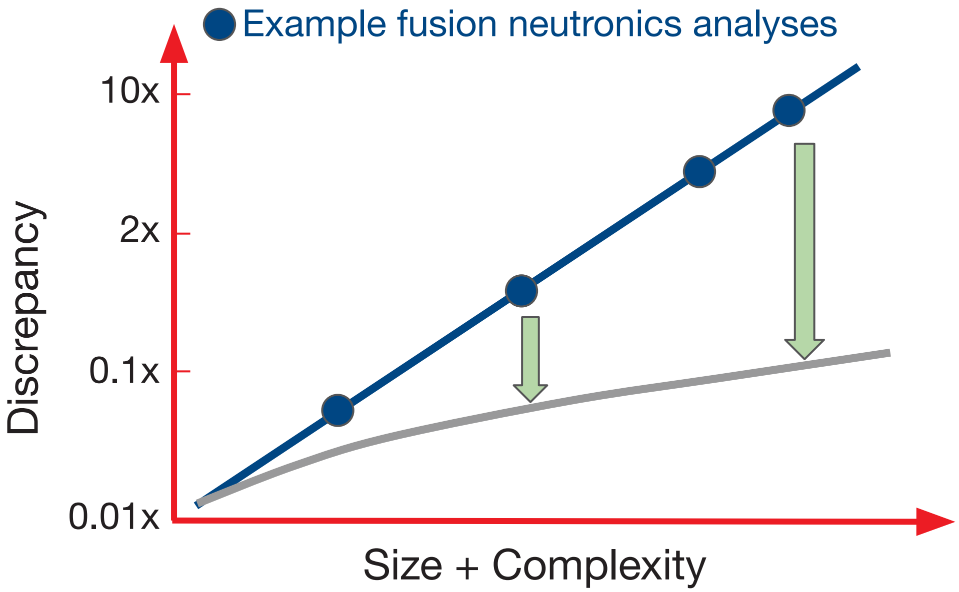
To have confidence in our predictive modeling tools we have to find better agreement between experiments and simulations for large complex systems.



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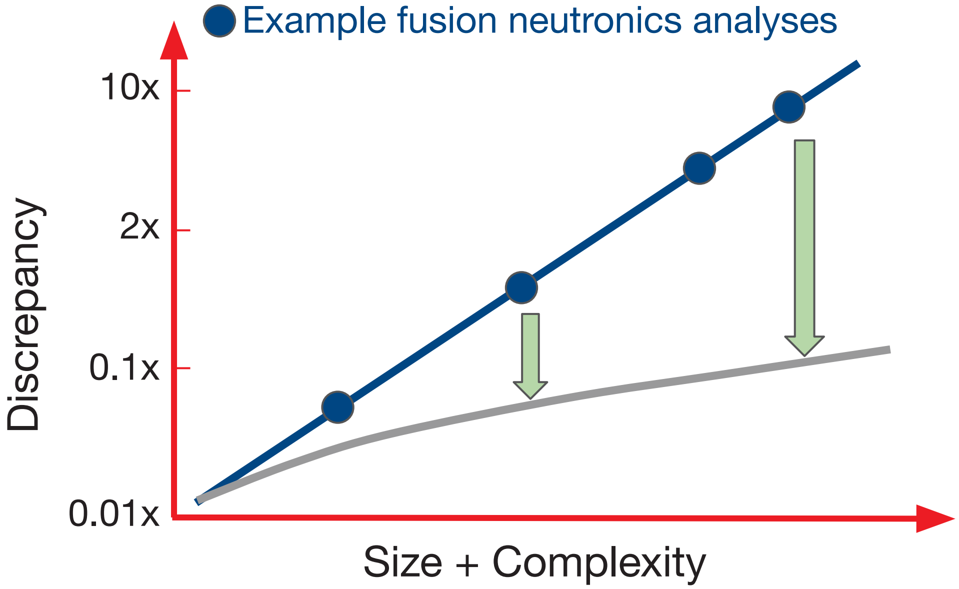

We need powerful, extensible, integrated tools to make this tractable!

As it currently stands…

MIT PSFC

We don’t have a good sense of what the REAL uncertainties are in these analyses

→ **What are the engineering margins people need to work with?**

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We also don't have ways to easily find the biggest levers during design

→ **How can we change the design to make it better?**

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→ **What are the engineering margins people need to work with?**

We also don't have ways to easily find the biggest levers during design

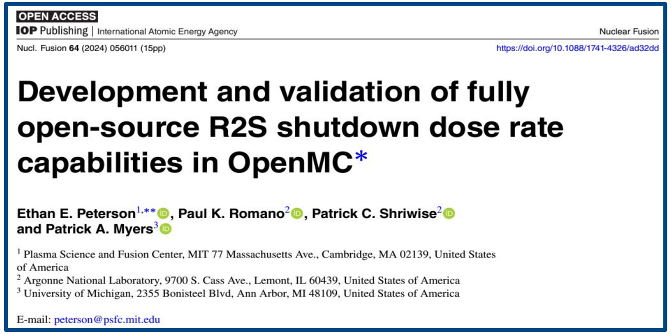
→ **How can we change the design to make it better?**

How can we facilitate and accelerate the "build, measure, learn" cycle when…

1. It takes forever to "build" the analysis with existing tools.
2. What we "measure" may not be correct (limited uncertainties).
3. What we "learn" is mostly binary i.e. "will it work" or "won't it work" with no additional feedback or margins.

What is the solution here?

Transport integrated UQ/SA techniques to handle the wide variety of responses in fusion



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Development and validation of fully open-source R2S shutdown dose rate capabilities in OpenMC*

Ethan E. Peterson[1,**], Paul K. Romano[2], Patrick C. Shriwise[2] and Patrick A. Myers[3]

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[2] Argonne National Laboratory, 9700 S. Cass Ave., Lemont, IL 60439, United States of America
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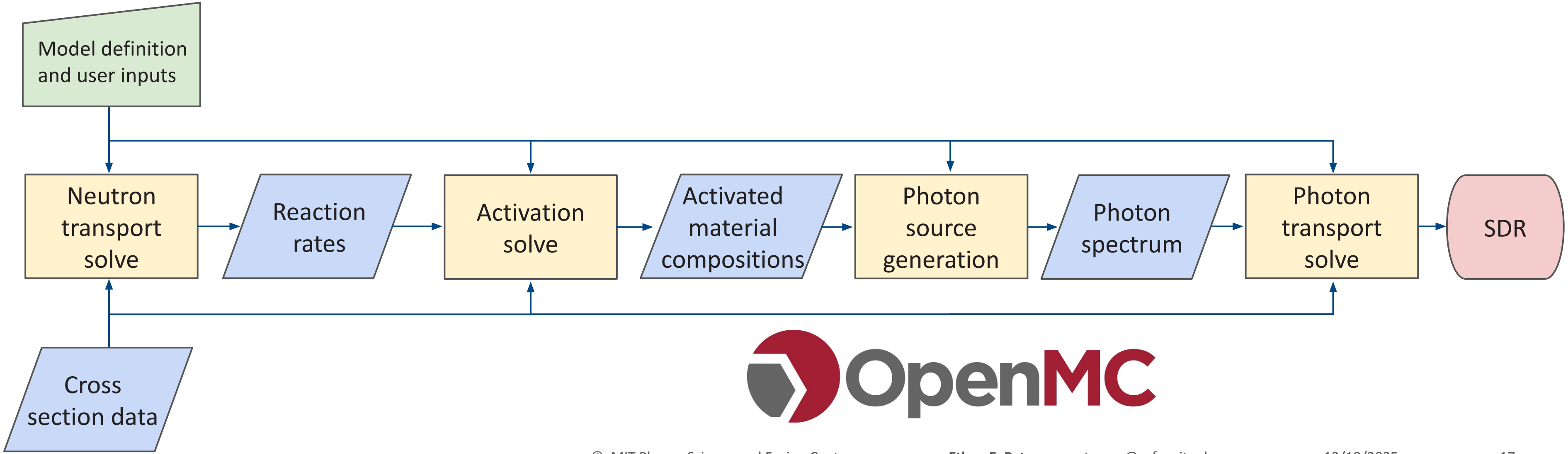
E-mail: peterson@psfc.mit.edu



OpenMC

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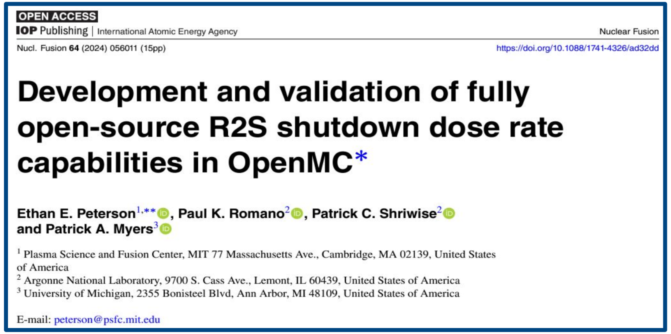
MIT PSFC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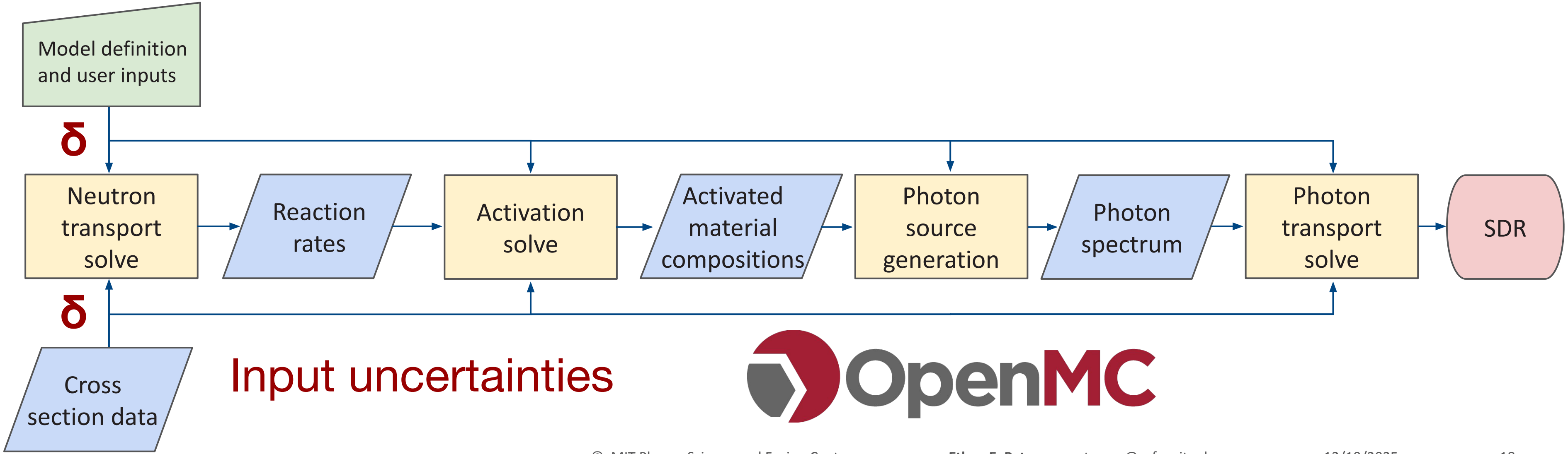

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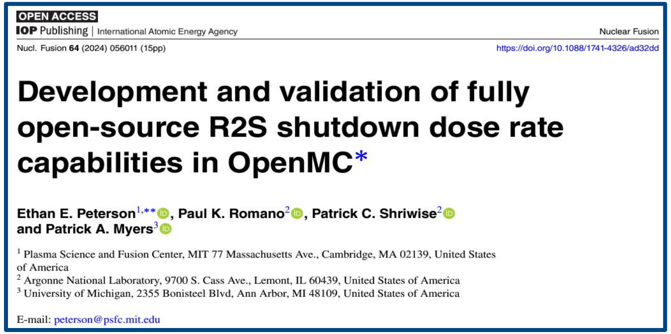
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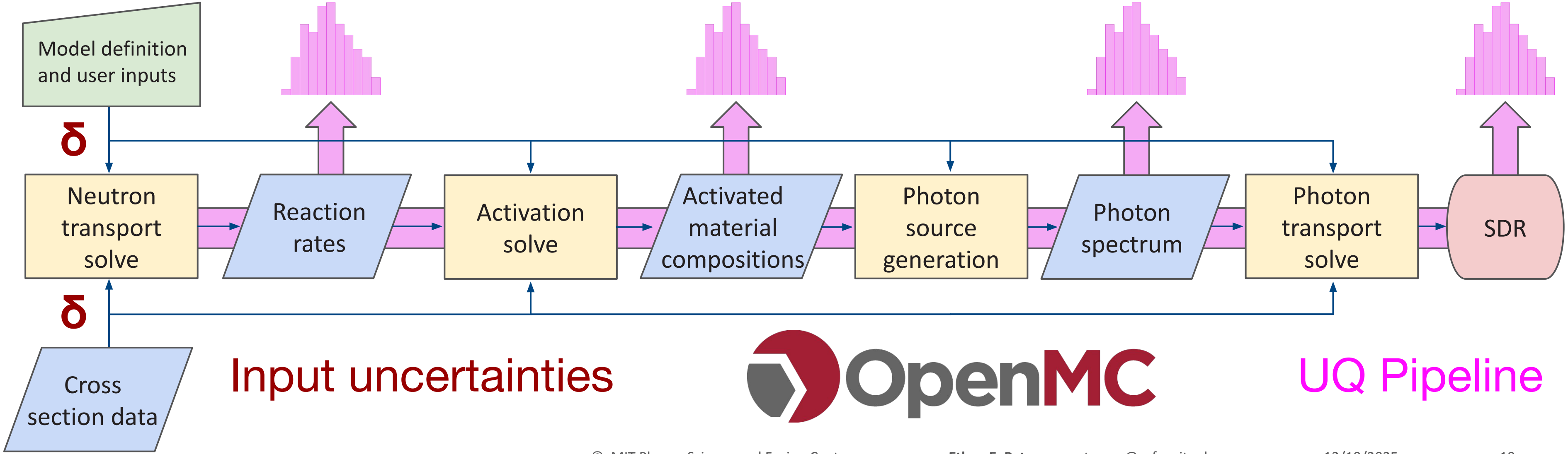

Transport integrated UQ/SA techniques to handle the wide variety of responses in fusion

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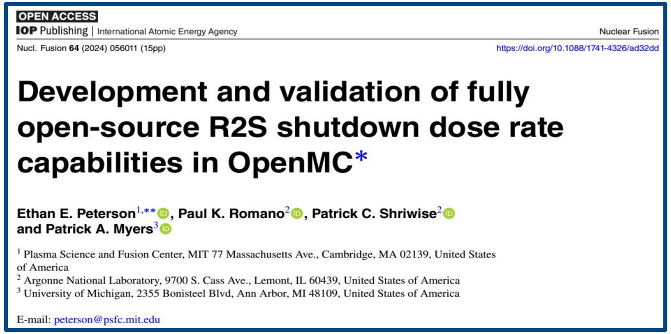
- Full control over all modules and interconnects
- Designed for exascale architectures
- Extensible for coupling with other applications
- Single source of truth for transparent V&V
- Open-source, community-driven ecosystem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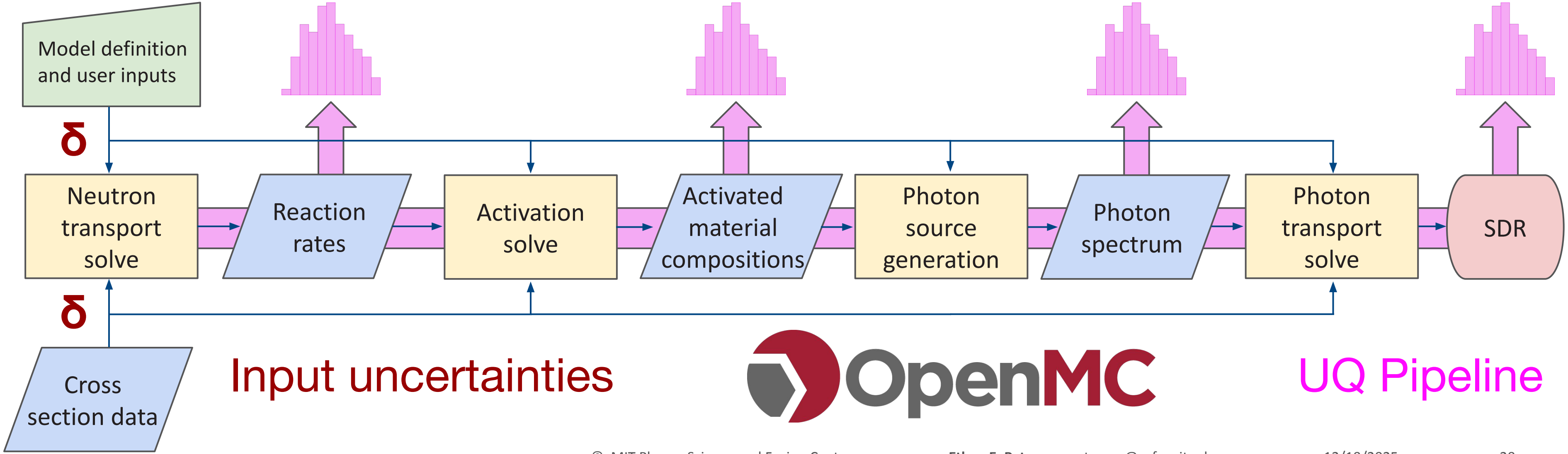
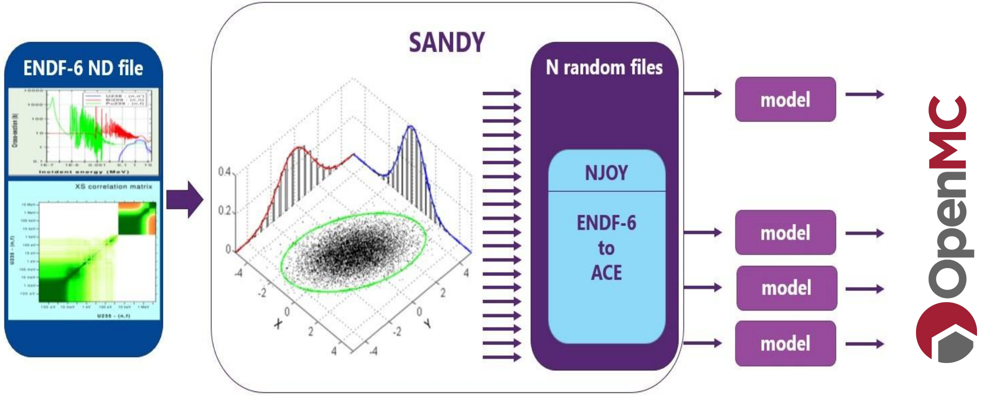


How do we actually conduct our UQ?

Total Monte Carlo (TMC) and Perturbation Theory



Captures nonlinearities, but can be computationally expensive

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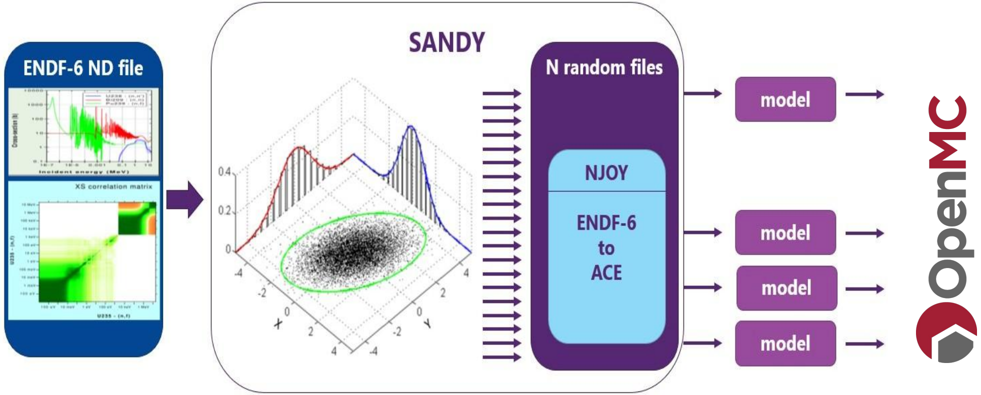

$$S_{R,\alpha} = \frac{\langle f_{R,\alpha}, \psi \rangle + \langle \psi^\dagger, Q_\alpha \rangle - \langle \psi^\dagger, H_\alpha \psi \rangle}{R}$$

Captures nonlinearities, but can be computationally expensive

Can be done in a single simulation, but requires the adjoint flux, and transport operator perturbations

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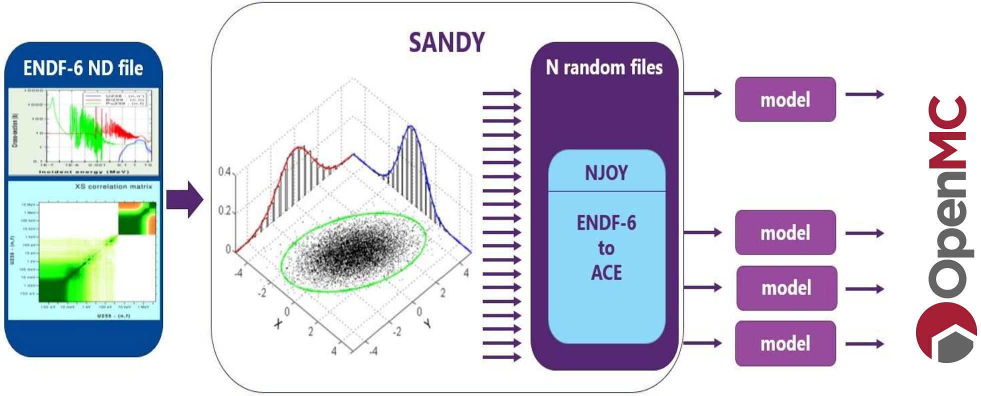

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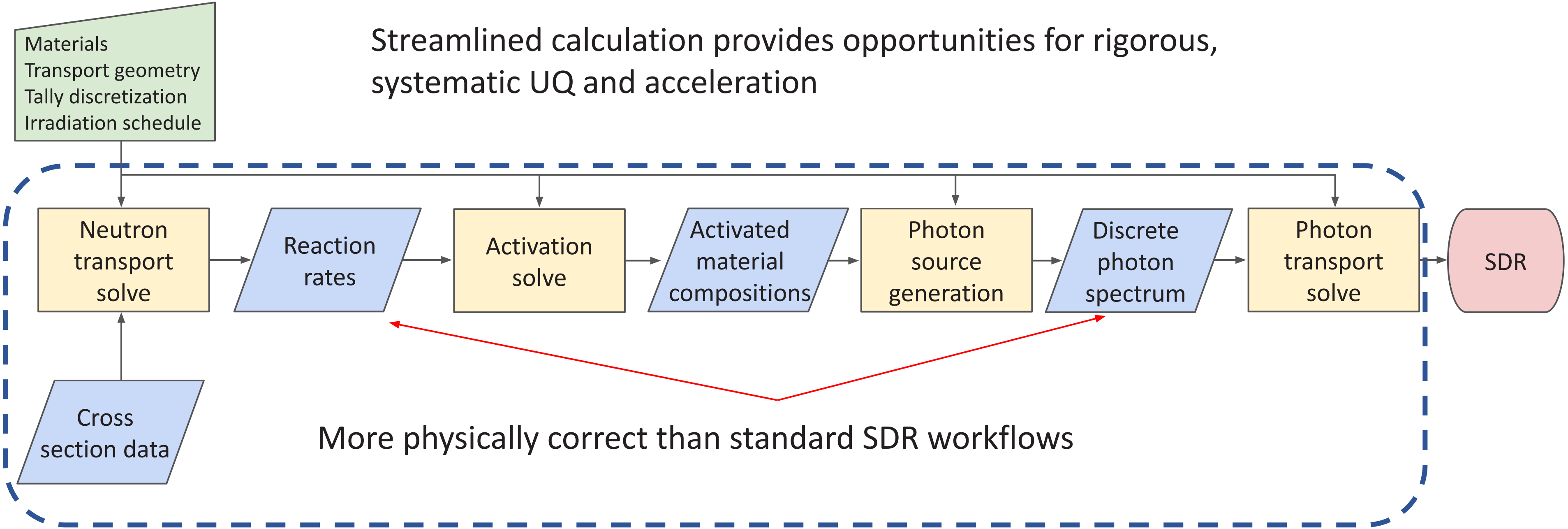
Can be done in a single simulation, but requires the adjoint flux, and transport operator perturbations

These are questions of **<u>performance</u>** and **<u>infrastructure</u>**

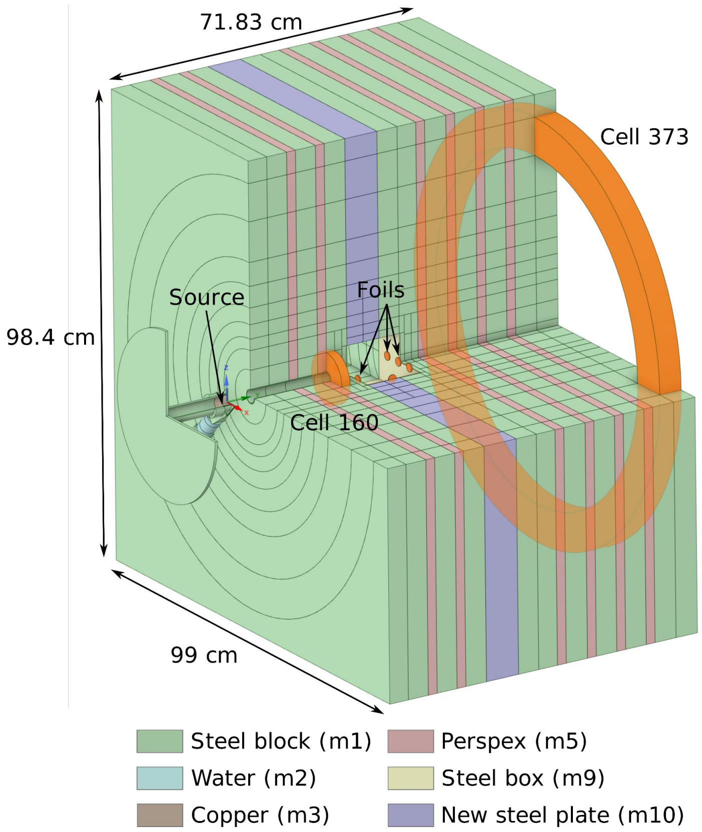
Streamlined OpenMC SDR infrastructure reduces errors and enable rigorous uncertainty quantification

Streamlined calculation provides opportunities for rigorous, systematic UQ and acceleration



Transport + Activation + Photon source generation + Photon transport

Validation of OpenMC workflows with the FNG shutdown dose rate benchmark from SINBAD



Frascati Neutron Generator (FNG)

Table 2. Irradiation schedule for the FNG shutdown dose rate experiment, campaign 1.

Source (neutron/s)	Duration (s)
2.32×10^{10}	19 440
—	61 680
2.87×10^{10}	32 940
—	54 840
1.90×10^{10}	15 720
—	6360
1.36×10^{10}	8940

E. E. Peterson *et al* 2024 *Nucl. Fusion* **64** 056011
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Demonstrates/validates capabilities typically obtained by coupling MCNP and FISPACT in a single, free, open source package, with reduced approximations

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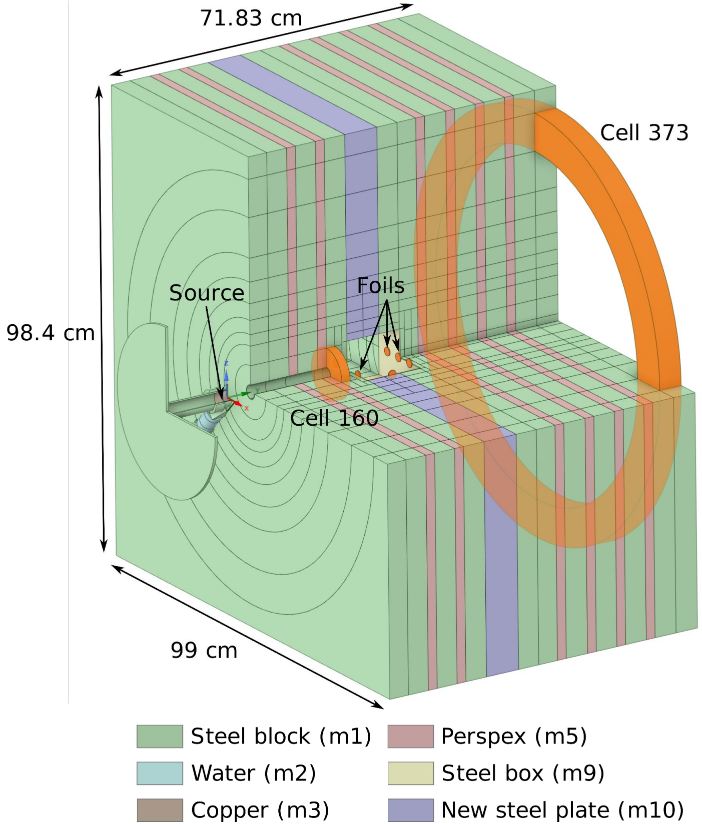

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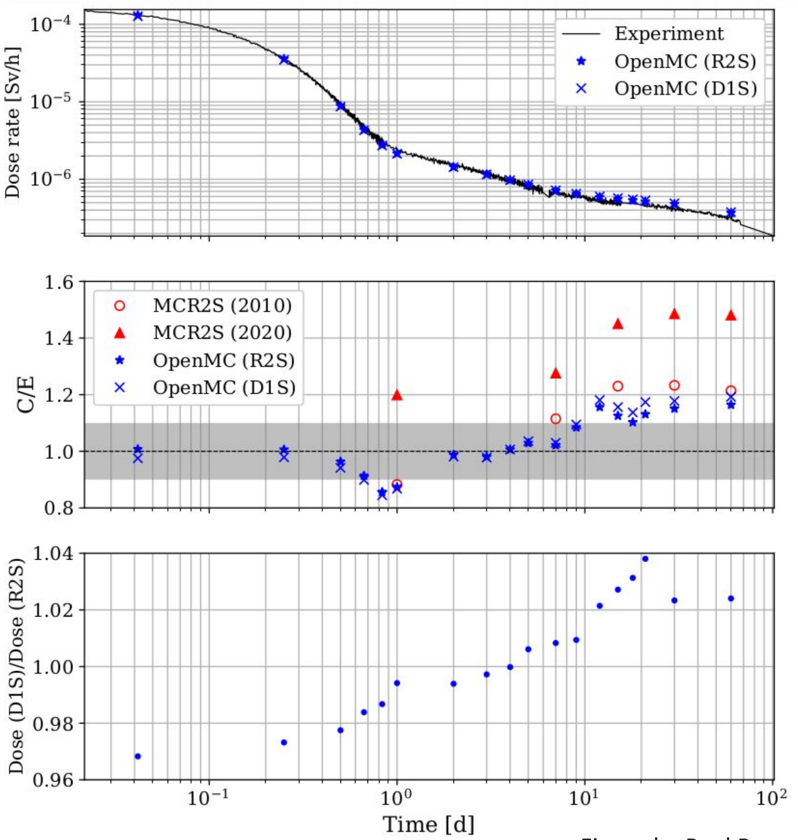


Figure by Paul Romano

Do these workflows apply beyond benchmarks?

What impact could they have on design of future devices?

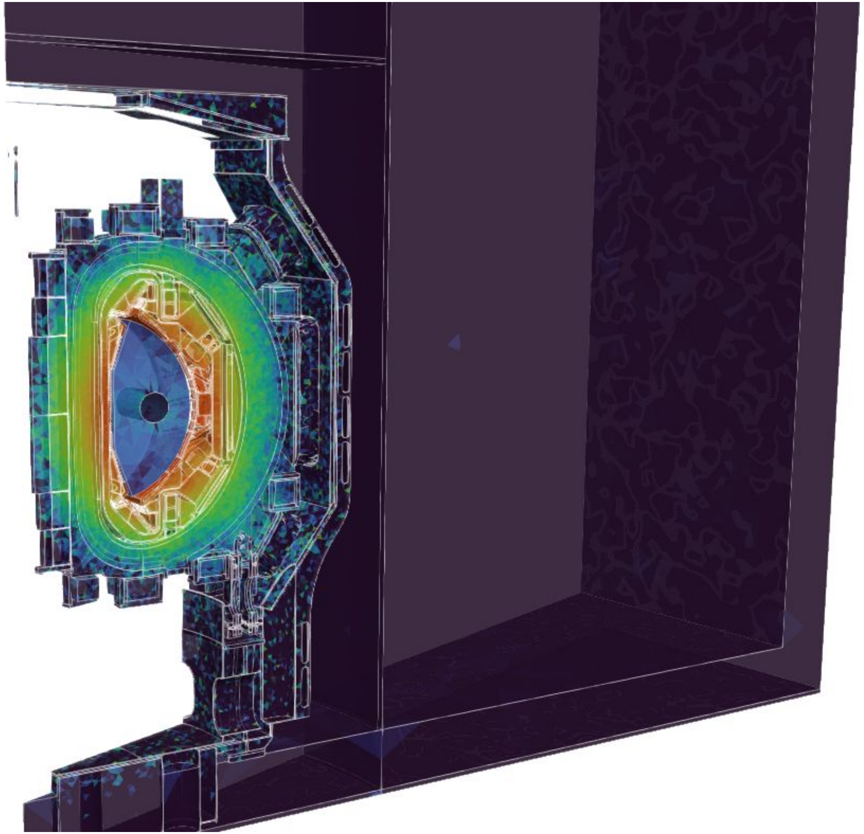
Preliminary SPARC tokamak analysis in OpenMC

- Discontiguous UM 20° model
- 794,974 linear tets
- 413,632 triangles
- 268,529 nodes
- 1,811 volumes
- 28 materials
- 37 nuclides

Enabled by new XDG library

https://github.com/xdg-org/xdg

Work on SPARC calculations supported by Commonwealth Fusion Systems under RPP036: Nuclear Modeling



What is XDG?

XDG

The Accelerated Discretized Geometry (XDG) library is an API for OpenMC to interface with different mesh libraries and leverage high-performance raytracing libraries for Monte Carlo operations.

P. Shriwise *et al.* SOFE 2025 poster

OpenMC

XDG: A library intended to connect CAE-based neutronics workflows (e.g. Attila4MC, Cubit, Symmetrix) to OpenMC

Mesh Interfaces

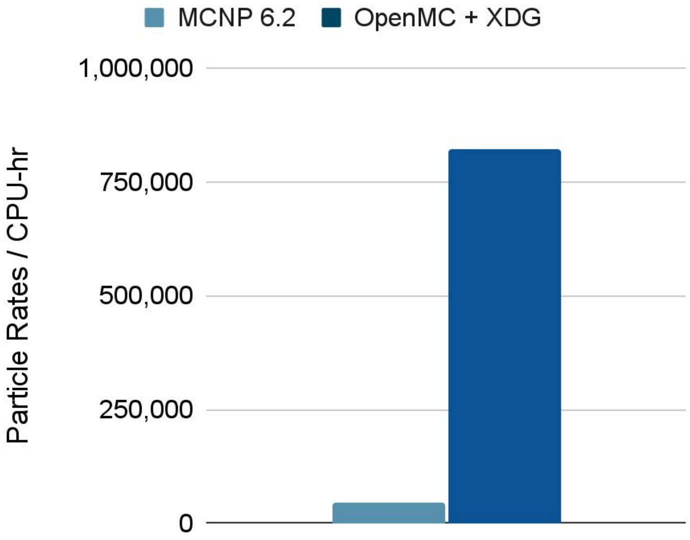
MOAB libMesh mfem DAGMC

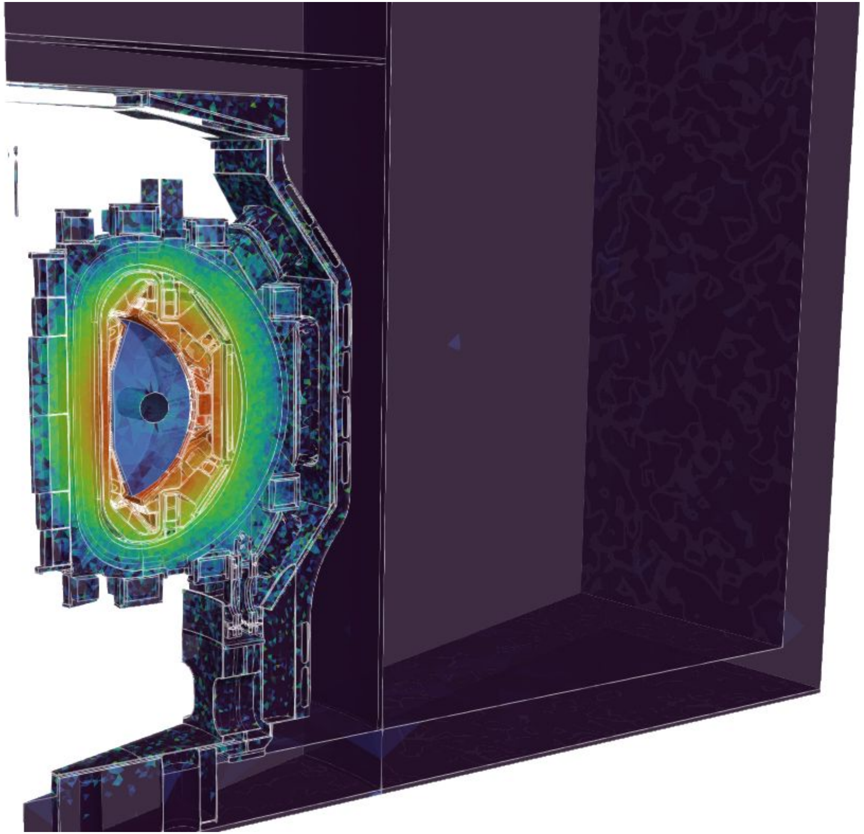
Raytracing

CPU: intel eMBRee GPU: GPRT

Q: Why XDG? A: Performance and deployability

SPARC magnet heating within +/- 5% of MCNP at >20x speed
- MCNP (96 CPU for 23 hours on AWS GovCloud)
- OpenMC (my laptop for less time for free)





MCNP results by CFS
A. Johnson et a., Calculation of Magnet Heating Profiles Using Advanced Unstructured Mesh Variance Reduction Techniques, 15th ITER fusion neutronics meeting, April 2024.

Nuclear heating is just the first example, shutdown dose rates are available as well

MIT PSFC

Direct 1-step (D1S) workflow enabled in OpenMC

Transport decay photons instead of prompt in a single simulation

Must satisfy approximations of no burnup and dose rates dominated by single step pathways

```python
from openmc.deplete import d1s

model = openmc.Model()
dose_tally = openmc.Tally()
...
model.tallies = [dose_tally]
model.settings.use_decay_photons = True

nuclides = d1s.prepare_tallies(model)
factors = d1s.time_correction_factors(nuclides, timesteps, source_rates)

model.run(apply_tally_results=True)

tally = d1s.apply_time_correction(tally, factors, time_index)
```

4 additional lines of Python from an existing OpenMC model

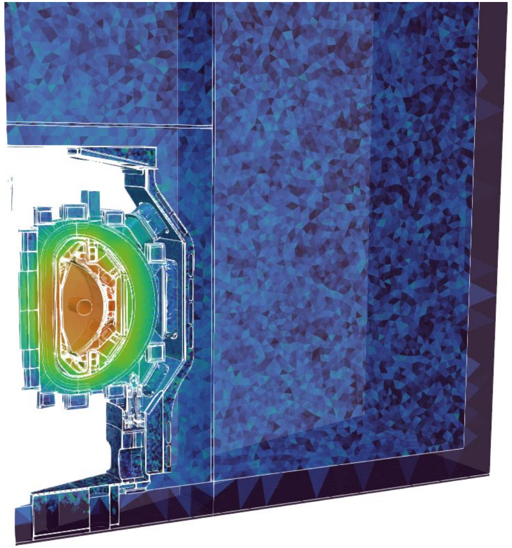
P. K. Romano, B. Ebiwonjumi, P. C. Shriwise, and E. E. Peterson. Implementation of the D1S Methodology for Shutdown Dose Rate Calculations in the OpenMC Monte Carlo Particle Transport Code. *FST* (accepted 2025)

D1S provides dose rates for arbitrary irradiation scenarios from a single simulation

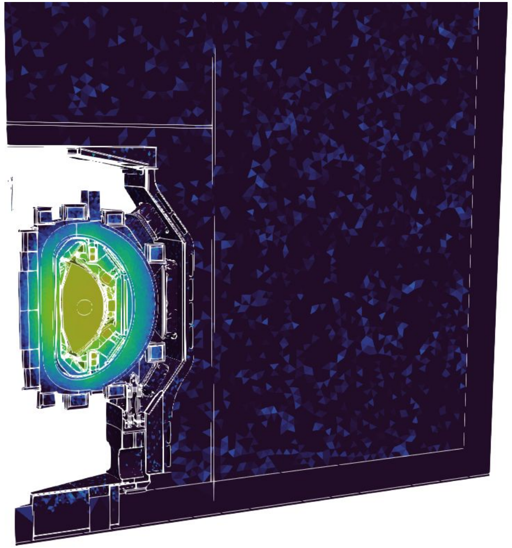
MIT PSFC

Workflows are up and running on realistic SPARC models

Shutdown dose rates with D1S in OpenMC computed on the right for multiple time cooling times after a single SPARC pulse (PRD) from one OpenMC simulation



Time 1



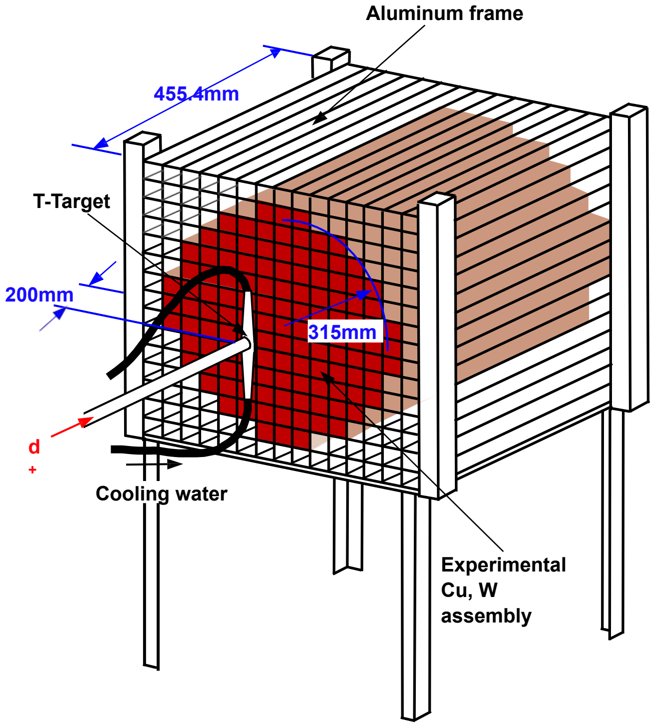
Time 2

Where does our UQ fit in?

Nuclear heating uncertainties even in simple benchmarks have real implications for power plants

MIT PSFC

FNS benchmarks for flux spectra and heating in single materials from neutrons and photons with a D-T neutron source



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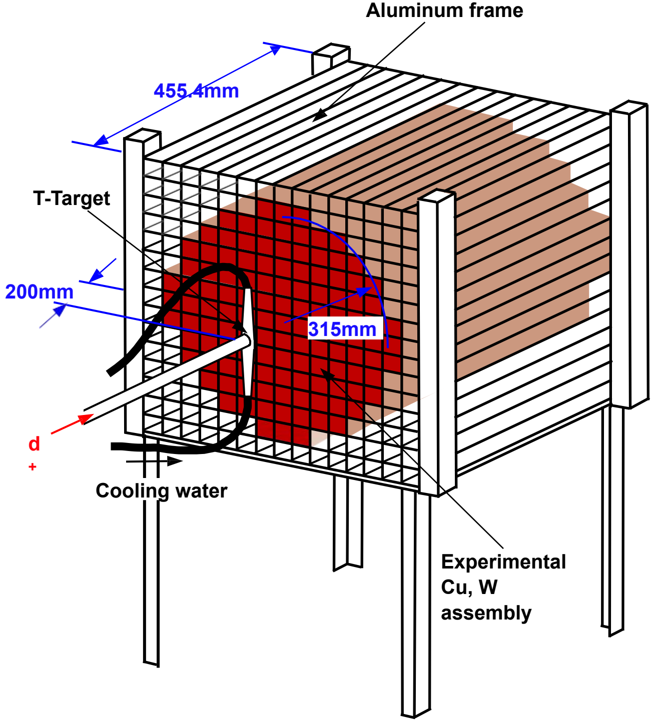

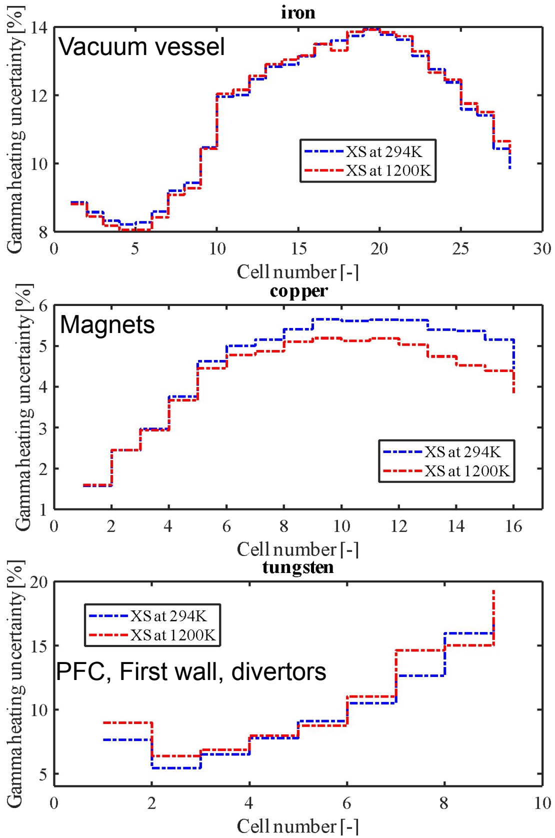

Uncertainty of photon heating due to neutron cross-sections

Nuclear heating uncertainties even in simple benchmarks have real implications for power plants

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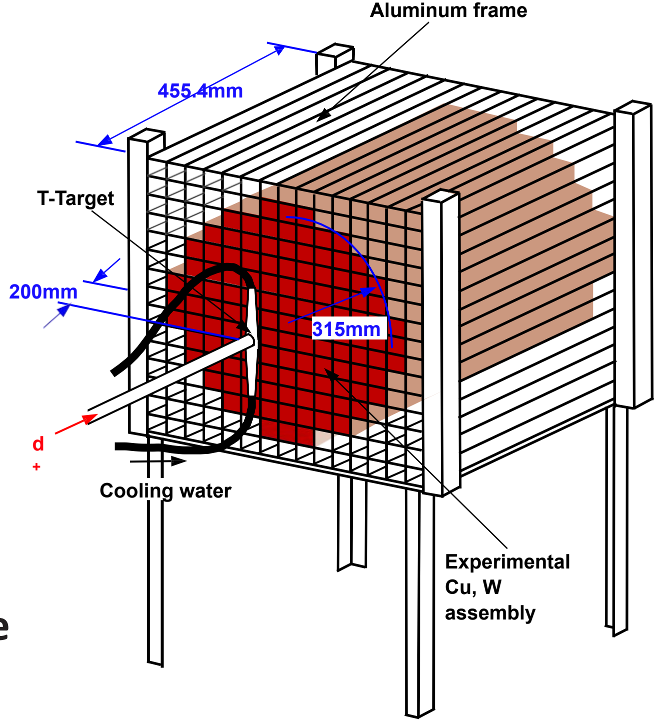
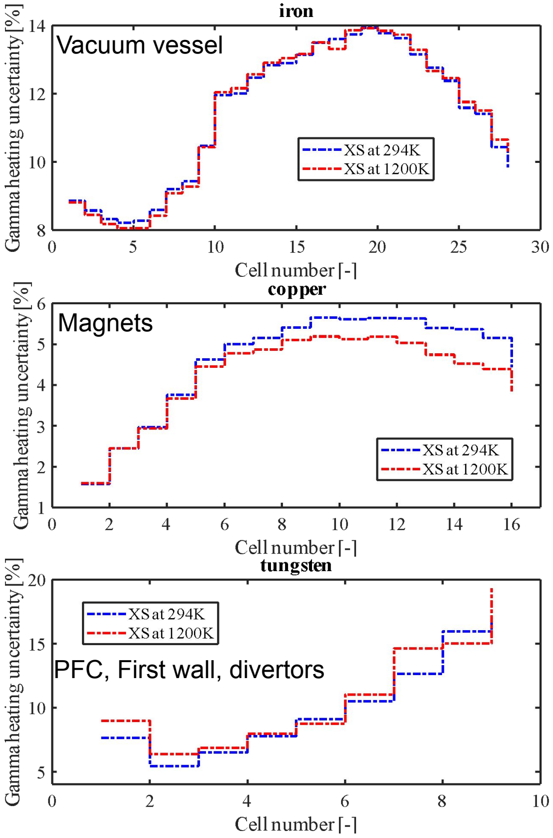
More integral benchmark experiments for fusion are desperately needed!

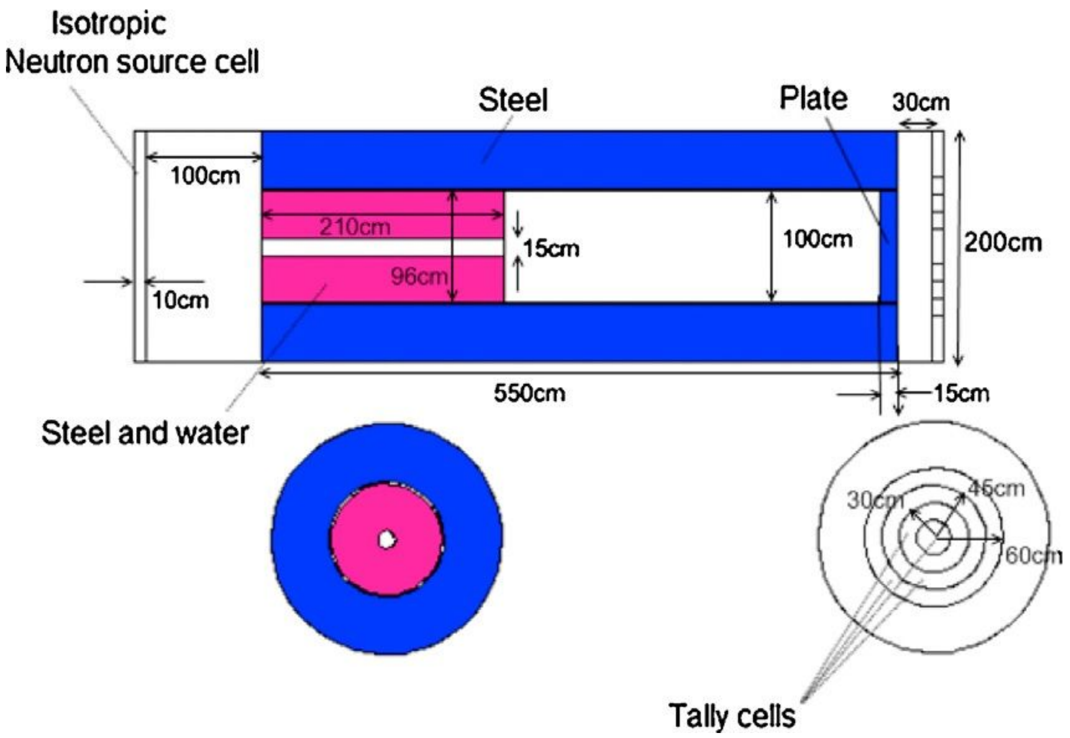




Uncertainty of photon heating due to neutron cross-sections

Shutdown dose rate uncertainties

Propagation of neutron cross-section uncertainties in ITER port plug computational shutdown dose rate benchmark



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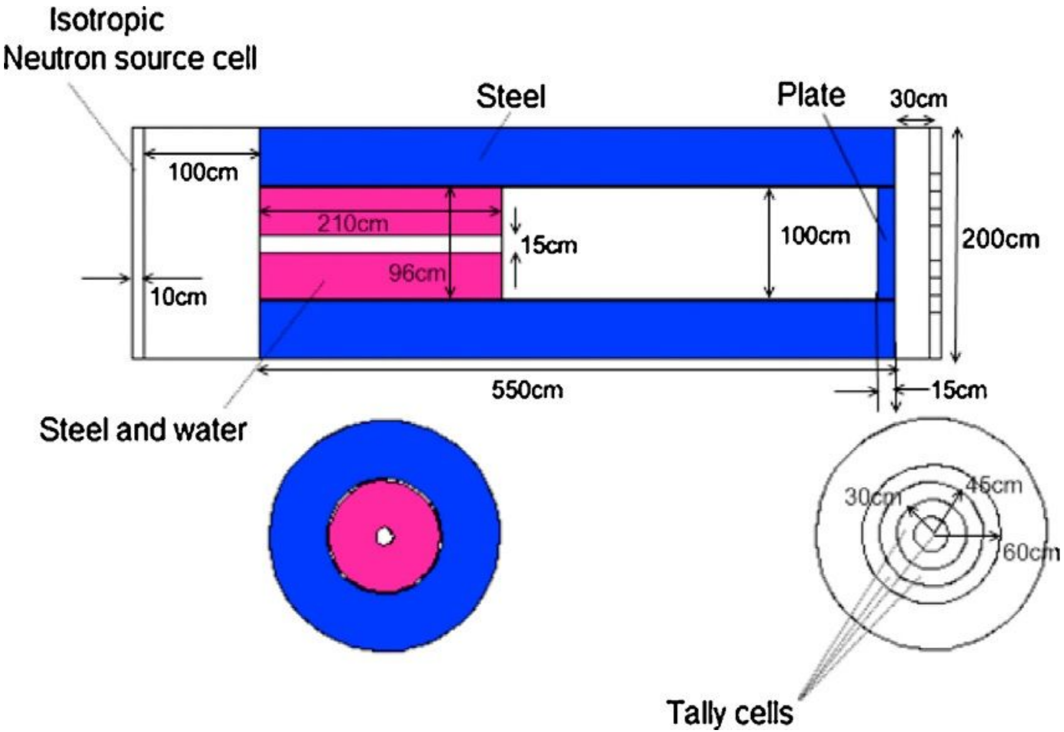

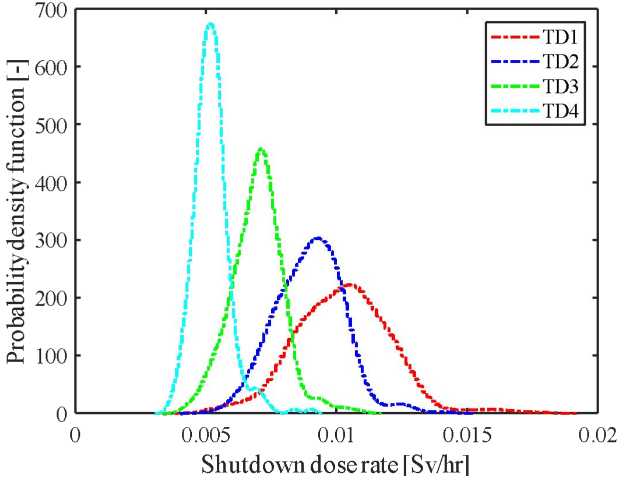

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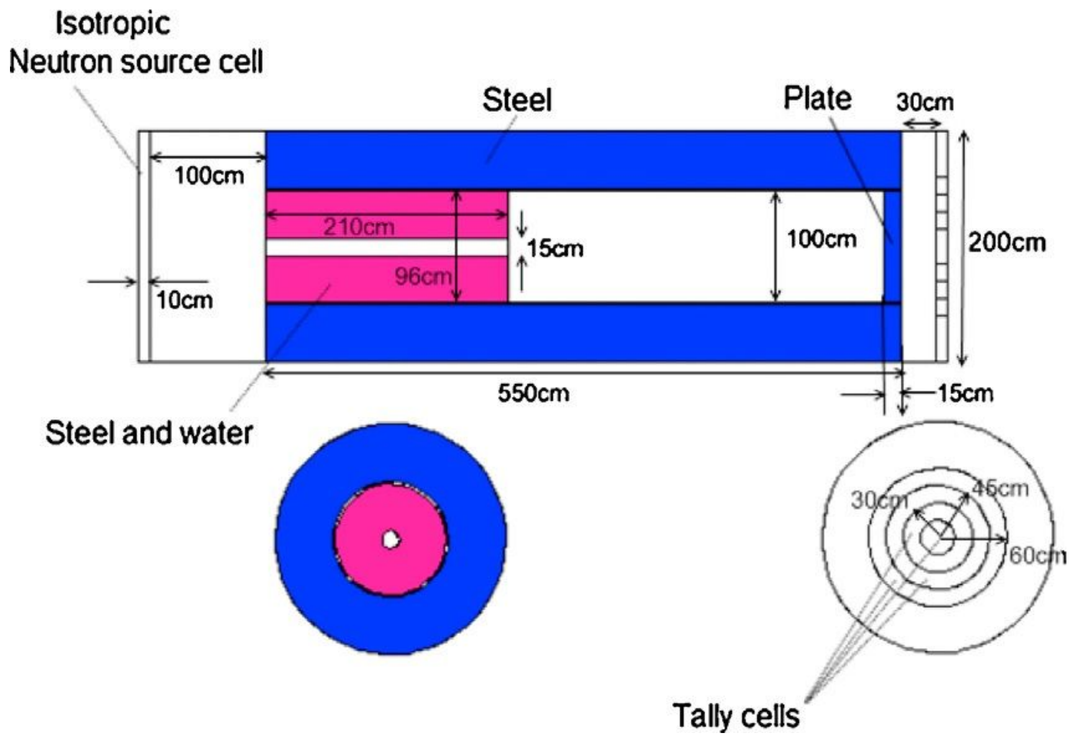
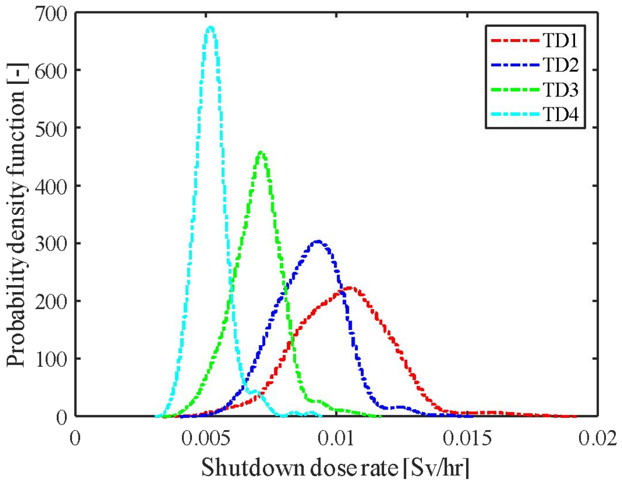
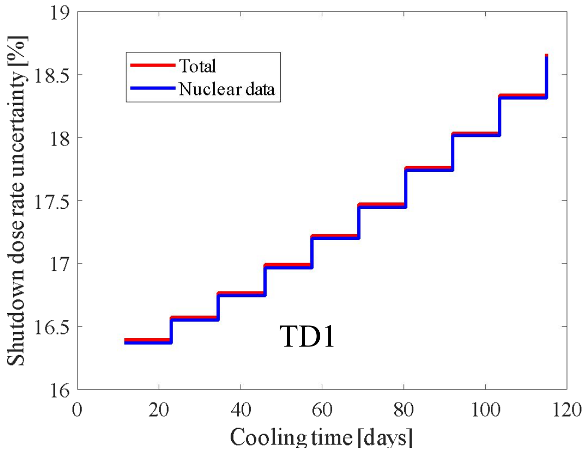
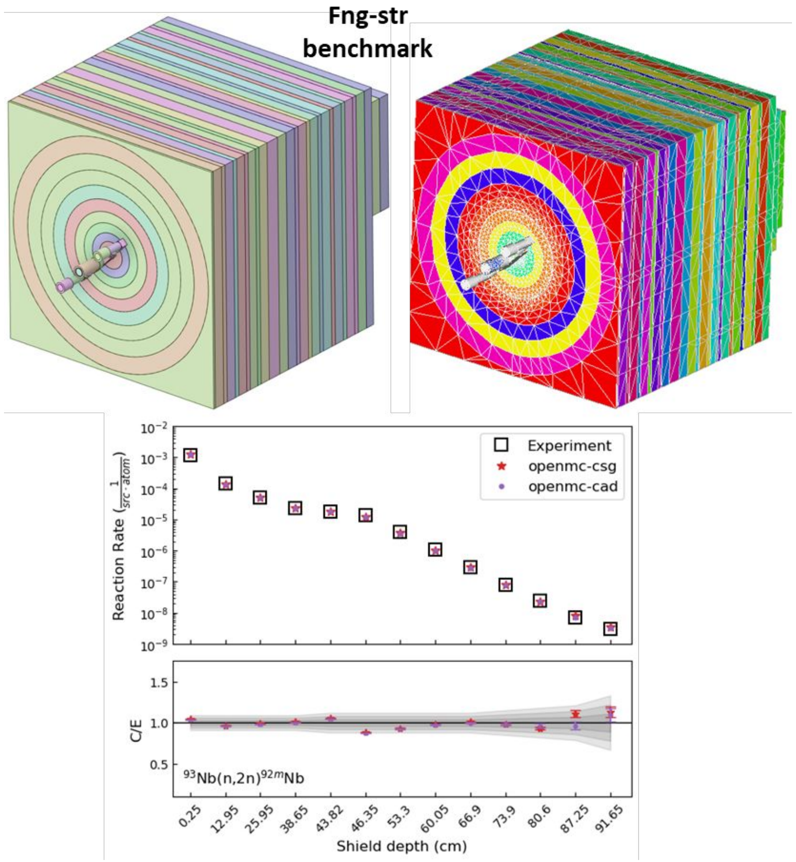






Moving towards UM transport & methods V&V

- Focus on benchmark definition in neutral format with CAD for geometry
- Automate CAD-to-mesh and CAD-to-CSG workflows for validation
- Exercise on existing benchmarks
- Extend to include analytic and computational benchmarks including transmutation coupled responses and new experiments
- Automate test suite to run on OpenMC release
- See poster by Stefano Segantin for more info



What impact can this have for the fusion community?

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- Permissive license opens options for compute platform from laptops to exascale machines without export control restrictions saving time and cost
- Fastest way to onboard new talent and train them to make impact in both the public R&D space or the private sector

Conclusions

- Comprehensive UQ for fusion power plant design starts with addressing the necessary workflows and analysis pathways.
- Transport-integrated UQ is enabled by both infrastructure improvements as well as performance improvements for both TMC and perturbation theory based methods.
- OpenMC is rapidly nearing “feature completeness” for fusion technology development and has a compelling performance narrative thanks to XDG.
- UQ pipelines are critical to making good engineering decisions
- Scalability and deployability are a huge benefit - runs on laptops to exascale and everything in between

Thank you!